Damage Evaluation of Slate
Using Nonlinear Acoustic Resonance

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Introducing nonlinear acoustic resonance at the K.U.Leuven was a tough job. After a struggle for money, equipment and a room where I didn't bother anybody (except the neighboring pigs) by the annoying dBs, I managed to bring together the necessary pieces and run my own nonlinear resonance experiments. The setup is very similar to what exists at EES-4, LANL. Differences are (1) a noncontact source in the form of a low-frequency speaker (2) completely free conditions for the sample (3) fft and lock-in capabilities using a 16 bit MIO-16-X card from NI and LabVIEW (4) built-in post-processing analysis using LabVIEW's polynomial fits.

In the frame of a combined scientific-technological project between the University and a Flemish building company (Eternit), my task is to study damage and its evolution in slate roofing tiles. These tiles are composed of Portland Cement as the main ingredient. Mineral additives and synthetic organic fibers are added to achieve a high-quality product. I started with a complete characterization of the material. Static, dynamic, and hygric material properties were derived from a wide range of experiments. Main con-clusions were: (1) Young's modulus around 20 GPa, density 1800 kg/m^3; (2) the material has a *Q* similar to Sandstones (100); (3) the anisotropy is of the order of 10%; (4) the material is vapor tight and has relatively fine pores (1-100 nm). Moisture transport mainly occurs through watervapor diffusion.

As for the nonlinear acoustic characterization, I observed similar behavior as in sandstones. Because of the geometry of the product, the measured resonance curves correspond to the one of the bending mode of a plate, typically around 300 Hz. At increasing amplitudes, a softening modulus results in a shift of the resonance frequency towards lower values. The shift is linear at low excitation (up to a voltage of 4 V) and quadratic for higher forcing amplitudes (from 4 to 10 V). As the dBs generated by the speaker in the high-amplitude range is really unbearable (even for pigs), I concentrated on the linear shift only (up to 4 V input). I defined the nonlinear parameter "alfa" to be the proportionality coefficient in the linear relation between the shift and the measured peak acceler-ation. For undamaged material samples, the value for alfa typically is around 0.015 [units 1/(m/s^2)]. In a first series of experiments, hammer impact was used to induce progressive damage. Without causing any visible damage in the sample, it was easy to observe an increase of alfa by a factor 25. Since there were no changes in the experimental set-up, this can only be attributed to an increase of microcrack density. The cor-responding decrease of the linear resonance frequency was about 5%. The linear *Q* reduced by 40%. In a second series of experiments, we cycled several slate samples through quasi-static stress-strain loops with maxima close to the maximal bending stress (around 20 MPa). Doing so, it was easy to measure and control the static E-modulus, which can be used to quantify the damage state by defining $D=1 - E/E_0$, with E_0 the value of the quasi-static modulus in the initial state. Linear and nonlinear parameters were measured for increasing D-values (0-1). Again, we observed a rapid increase of the non-linear "shift" parameter and only a small to modest decrease of the linear parameters. At the formation of macrocracks, D=0.75 and the nonlinear coefficient increased by a factor of 1000. The values of the 3rd harmonic which is quadratic in the fundamental acceleration amplitude, showed a similar increase. The second harmonic did not increase drastically till macrocracking occurred.

These preliminary experiments clearly show that nonlinear acoustic resonance is a promising tool for NDT of quasi-brittle materials. Future goals include monitoring linear and nonlinear behavior of slate after natural and accelerated hygrothermal aging.